Highlights of Constellation–X Reflection Grating Spectrometer Technology Development

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Abstract

Constellation-X is a high-throughput high-resolution spectroscopy mission and a Great Observatory of NASA's Beyond Einstein program (White *et al.* 2005; White *et al.* 2004; Tananbaum, *et al.* 2004). The Reflection Grating Spectrometer (RGS) on board Constellation-X provides high resolution X-ray spectra over 0.25-2.0 keV. The instrument's two components (a grating array and a detector readout array) require significant technological advances to meet the Constellation-X requirements for effective area and spectral resolution. We review the technology status, recent achievements and challenges of the Con-X Reflection Grating Spectrometer.

Hardware Overview of the Reflection Grating Spectrometer (RGS)

The Reflection Grating Spectrometer (RGS) (Flanagan, *et al.* 2004) has two components, the Reflection Grating Array (RGA), which intercepts and disperses the light exiting the Soft X-Ray Telescope (SXT) mirror modules, and the RGS Focal Plane Camera (RFC), which reads outs the dispersed spectrum (Figure 1). The Constellation-X mission reference configuration has four telescopes, each with its own RGA and associated RFC. The RGA consists of ∼50 modules, each containing ∼13 identical gratings arranged in an off-plane (conical diffraction) configuration. The RFC, an array of X-ray CCDS, has a Zero Order Camera (ZOC) which reads out the reflected image, and a Spectroscopy Readout Camera (SRC) which reads out the dispersed image. The ZOC can anchor the wavelength scale by tracking small aspect drifts. Overarching mission requirements of high effective area and high spectral resolution drive an agressive technology development program for the RGA and the RFC.

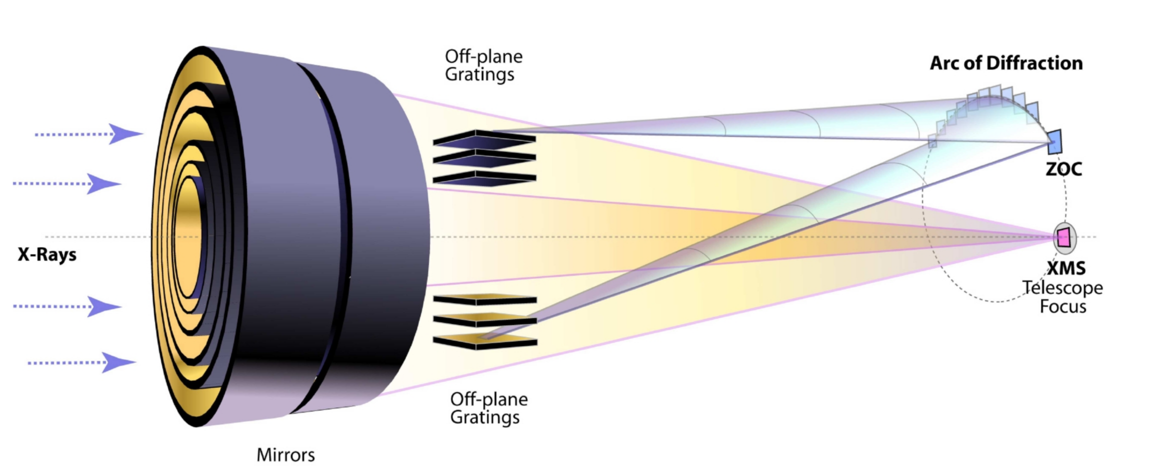

Figure 1: Reflection Grating Spectrometer (RGS)
Reflection gratings (in modules) are arrayed at the exit of the Soft X-ray Telescope. The X-rays are reflected to a zeroth order camera (ZOC), and diffracted to the Spectroscopy Readout Camera (SRC). The ZOC and SRC together make up the RGS Focal Plane Camera (RFC). For off-plane gratings, the readout follows an arc.

Heritage and Design Rationale of the RGA

Constellation-X RGA heritage includes the grating spectrometers onboard the XMM-Newton and Chandra Observatories, and on multiple x-ray sounding rockets. The Con-X RGA technologies build on these proven technologies. High effective area requires supersmooth (high reflectivity) gratings of large area with appropriate blaze and groove profile. High spectral resolution requires high line density, radial groove arrangement, and limits on flatness and alignment. Systems and production considerations drive the gratings design toward thin (<1mm) grating substrates, replicated gratings and modular packaging.

Heritage and Design Rationale of the RFC

X-ray CCDs have a heritage that includes the X-ray cameras onboard the High Energy Transient Explorer Mission (HETE) (Villasenor *et al.* 2003), the Chandra and XMM-Newton Observatories, the Advanced Satellite for Cosmology and Astrophysics (ASCA), and Suzaku (Astro-E2). Key features of the CCDs for the RFC include high readout speed, high quantum efficiency, and good energy resolution. To achieve this, the RFC technology development program is developing event-driven CCDs (EDCCDs) and investigating the use of a novel surface treatment (Lesser & Iyer, 1998; Burke *et al.* 2004) for back-illuminated devices.

Technology Status: Grating Fabrication, Testing and Modeling

The nominal fabrication requirements for Constellation-X off-plane gratings are given in Table 1. These requirements derive from the off-plane configuration proposed to satisfy the mission needs for effective area, spectral resolution, mass, etc. RGS technology development has achieved many of the fabrication requirements for individual gratings (for details see poster #12.15 in this session). Two independent parallel efforts assure an available grating source. The MIT "Nanoruler" (Konkola *et al.* 2003; Montoya *et al.* 2005) allows direct "writing" of the grating pattern, typically in ∼20 minutes. It has achieved the required size, mass, and line density and is undergoing modifications to allow the radial groove arrangement. However, the radial groove arrangement has already been achieved on gratings of appropriate line density through holographic lithography by Jobin-Yvon (JY) working with University of Colorado. Anisotropic etching of silicon (Franke *et al.* 1997; Chang *et al.* 2003) provides precise geometric control of line profiles, and has produced record-level diffraction efficiencies (Seely *et al.* 2005; see also Figure 5.) Ion etching has also been investigated to produce blazed grooves (McEntaffer *et al.* 2004). Two different replication methods (by Nano-imprint Lithography, or NIL) have been demonstrated to reproduce the groove shape satisfactorily (Chang *et al.* 2004)

Modeling and testing provide essential guidance and feedback to the development effort. Raytrace modeling (McEntaffer *et al.* 2003; Flanagan *et al.* 2004) and efficiency modeling are carried out at University of Colorado, SLAC and MIT. Efficiency tests have been performed at University of Colorado (McEntaffer, *et al.*, 2004; Osterman *et al.* 2004; Heilmann *et al.* 2004), and at synchrotron facilities at ALS and Brookhaven (Rasmussen *et al.* 2004; Seeley *et al.* 2005; see also Figure 5 and poster #12.02 in this session). A test of spectral resolution at University of Colorado (Osterman *et al.*, 2004 and Figure 6) has demonstrated $R=E/\Delta E \sim 500$ using a radial groove grating, and a large-size (100mm x 100mm) radial grating will be tested at the Panter facility in Germany in 2006 to demonstrate $R > 1000$.

The next challenges to be addressed by the RGA technology development program will include complexity above the single-grating level: assembly, mounting, aligning and testing of gratings in modules.

Technology Status: EDCCDs

A key feature of the CCDs for the RFC is high readout speed. It is achieved by fast clocking of the device, by pixel summation, and by utilizing an EDCCD scheme which allows reading out and digitizing only those pixels that contain signal charge (typically less than 1% of the total number of pixels). Very short readout time translates into the possibility of using very thin optical blocking filters, which would significantly boost the QE at low X-ray energies.

To obtain high quantum efficiency and good energy resolution at low energies, backside-illuminated (BI) devices will be subjected to a novel surface treatment (Lesser & Iyer, 1998; Burke *et al.* 2004). This new process has high fabrication yield due to its low temperature and simplicity (Burke *et al.* 2004). (High yield is essential to produce the high number of devices (∼60) needed for the four Constellation-X RFC layouts.) Representative sensors prepared for Suzaku show impressive performance, with superior quantum effciency and comparable spectral resolution to FI devices (Bautz *et al.* 2004). Chemisorption charging is compared with other backside processing in poster #12.03 in this session, which gives further details of RFC technology development.

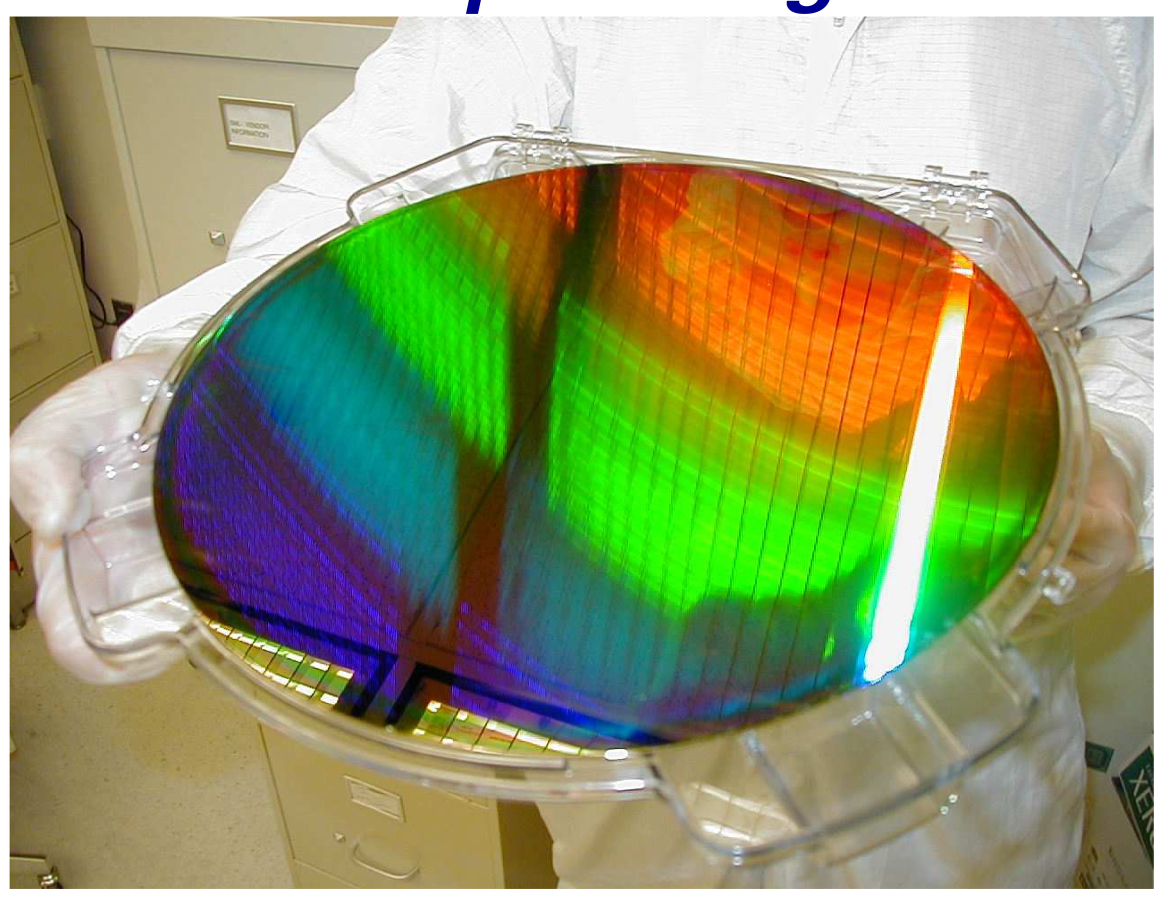

Figure 2: Large area, high line density, thin gratings
The Constellation-X off-plane gratings are nominally 100mm x 200mm in area, less than 1 mm thick, with line density ∼5800 lpmm. The grating pattern above (in resist) is 300 mm in diameter, 0.78 mm thick, with line density 2500 lpmm. Line densities up to 10,000 lpmm have been produced by the same group at MIT's Space Nanotechnology Laboratory.

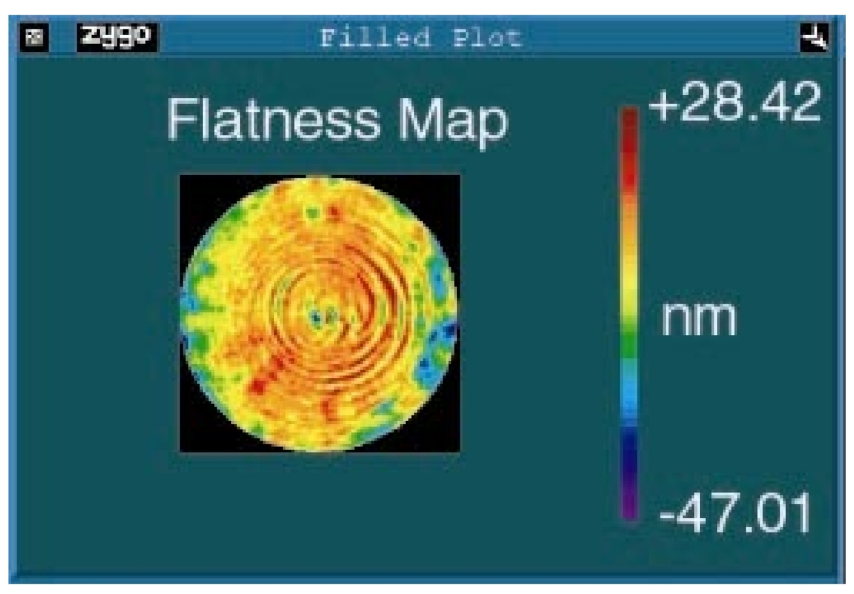

Figure 4: Record Flatness: 2 Arcseconds
The ability to make (and mount) flat gratings will impact the spectral resolution of the RGS. The interferogram above shows a wafer with a world record 2 arcsec flatness achieved through Magnetorheological Finishing.

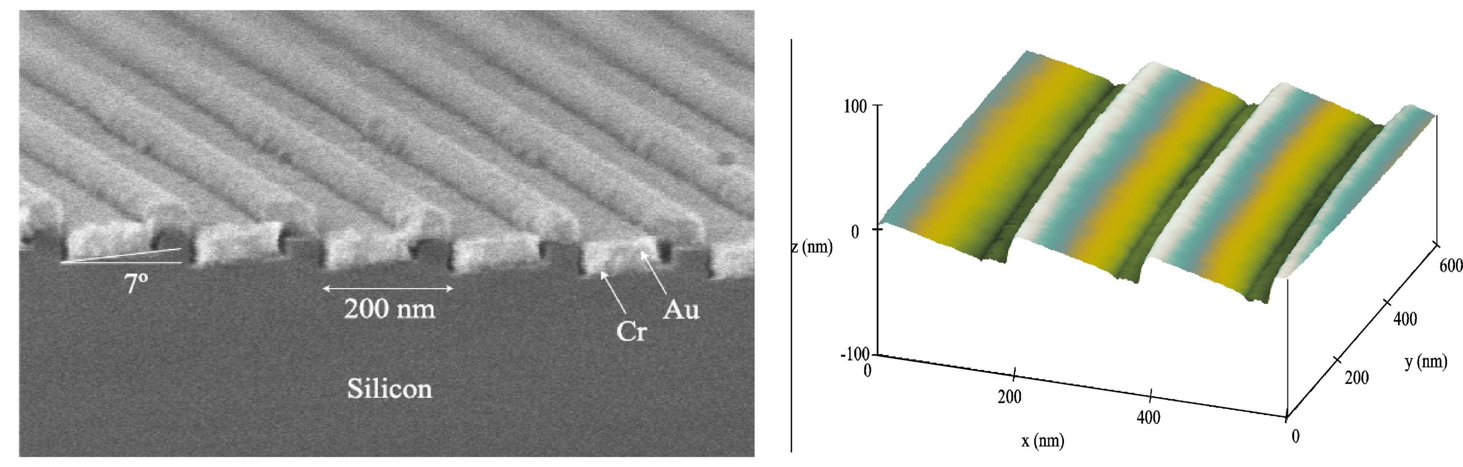

Figure 3: Anisotropic Etching: supersmooth gratings, precise groove shape
Anisotropic etching exploits the crystalline structure of silicon to give supersmooth gratings with precise groove shape. The figure at left is a Scanning Electron Micrograph (SEM) of a 5000 lpmm gold-coated master grating. The picture at right is an Atomic Force Micrograph (AFM) of a replica from a similar master. Two different replication methods have been successfully demonstrated.

Table 1. Fabrication Requirements for Off-Plane Gratings

Attribute	Requirement	Status	Comment
Size	100mm X 200mm	300mm diameter	Figure 2
substrate thickness	<1 mm	0.5 mm	Thin Si wafers; Figure 2
Line density	5800 lpmm	5000 lpmm	Up to 10,000 lpmm produced
Groove shape and smoothness	16.9 degrees (TBR), 0.5 nm	0.7–13 degrees, 0.2 nm	Anisotropic etching; Figure 3
Flatness	2"-24"[1]	2 arcsec	Figure 4
Alignment	2"-24"[1]	TBD	Current and Future work
Groove arrangement	radial	by holographic lithograpy	by Nanoruler in 2006
Replication	must preserve groove shape	by NIL	Two tested methods; Figure 3

1: Depends on spectral resolution requirement

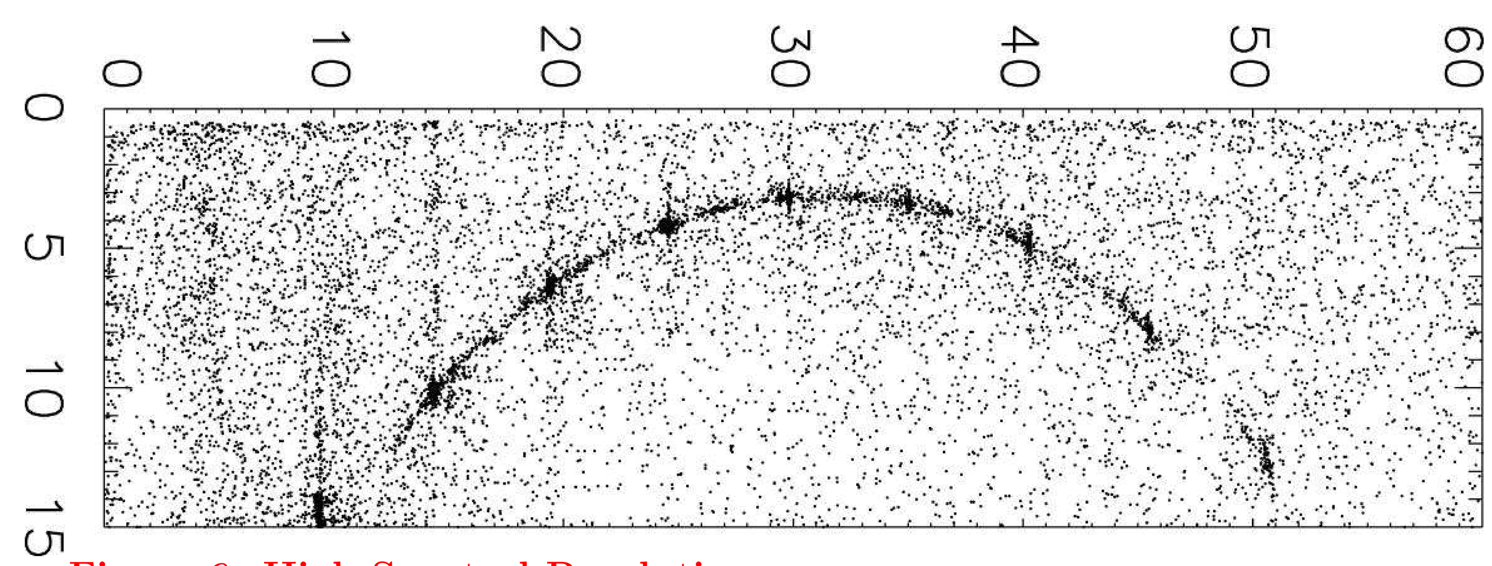

Figure 6: High Spectral Resolution.
An off-plane grating with a radial arrangement of grooves is used in a laboratory test of spectral resolution at the University of Colorado. Mulitple orders of the Cu-L line area visible in this concatenation of two images (Osterman *et al.* 2004). The spectral resolution was limited in the test by the quality of the telescope and environmental effects. A test at the Panter Facility in Spring 2006 is expected to demonstrate a resolution of 1000 or better.

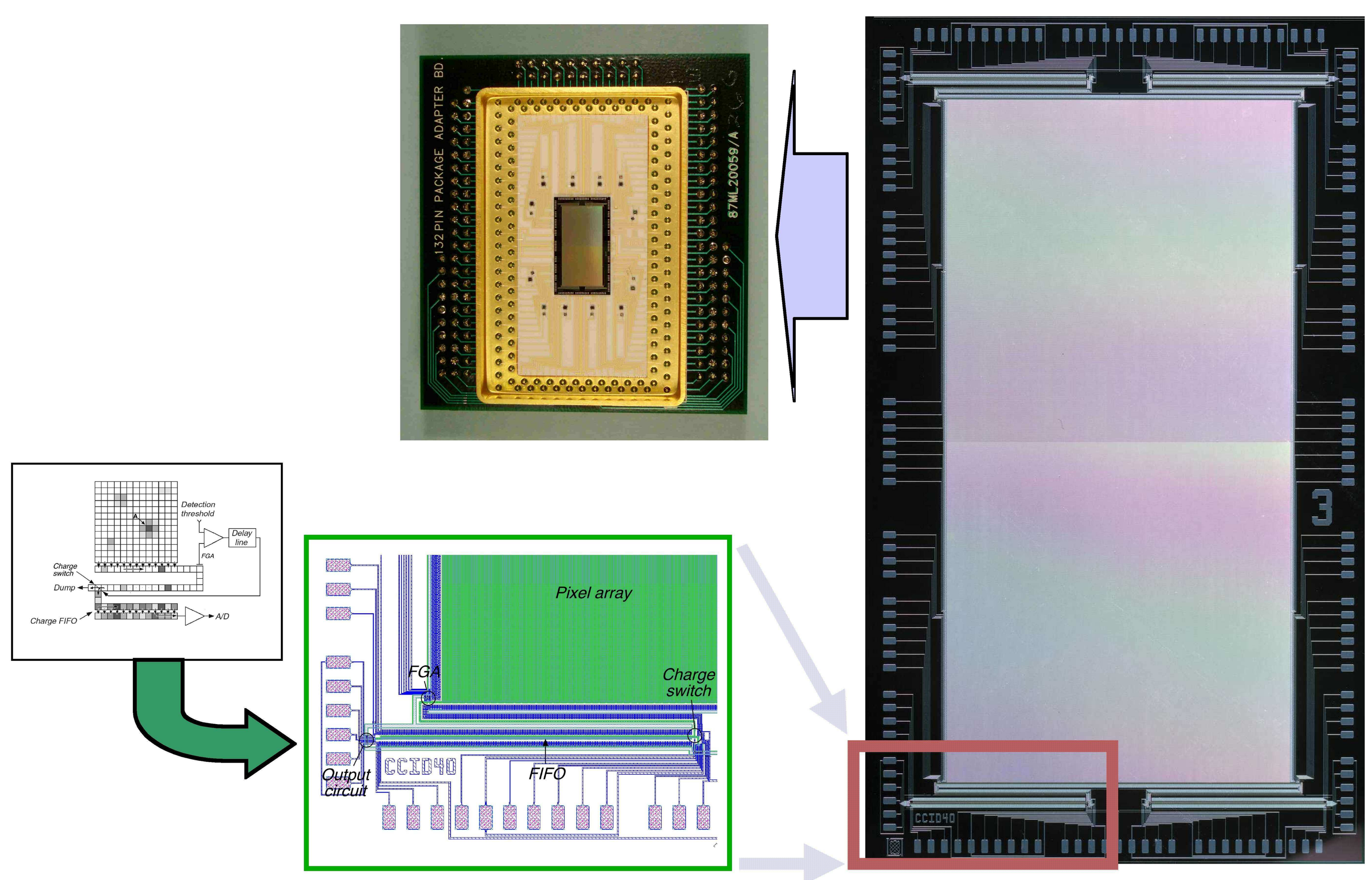

Figure 7: Event Driven CCD
Counterclockwise from lower left: Circuitry for the EDCCD allows selection and processing of only those pixels which contain signal charge (lower left); Gen 1.0 device fabricated at MIT Lincoln Laboratory with EDCCD circuitry (right); Packaged device (top left) is currently under test.

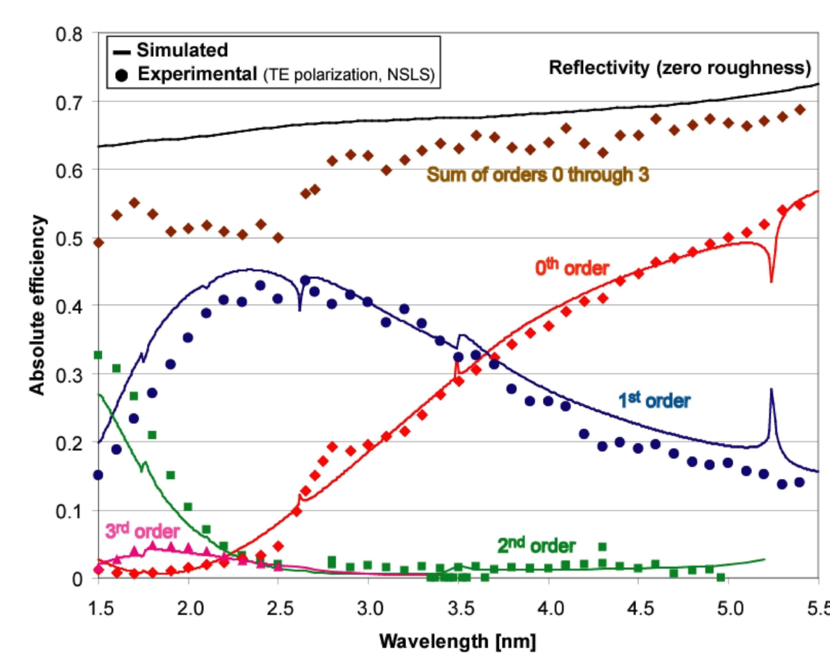

Figure 5: Record-level efficiencies
Raw TE efficiencies measured at Brookhaven (Seely *et al.* 2005) are overlaid on on a PCGrate model using AFM line profile measurements as input (courtesy J.M. Laming; see also Seely *et al.* 2005).

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